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Technology Impact Forecasting for Multi-Functional Composites

Danielle Soban
QUEEN'S UNIVERSITY BELFAST

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14. ABSTRACT
New aircraft are being required to meet increasingly stringent requirements, demanding that they be lighter, stronger, faster, and more environmentally friendly and sustainable, all at reduced operating costs. Multi-functional composites offer a possible solution to these conflicting design goals, and, through custom design and manufacturing techniques, could result in new materials that offer higher strength at lower weight. In addition, potential exists for bespoke capabilities, such as self-healing and damage detection, increased lightning strike protection, morphing wing shapes, and ice detection and prevention. The key challenge, and thus the novelty, of the research, is the extraction of meaningful data for a technology that is in its embryonic stage, and then being able to statistically extrapolate that data into a form that enables decision-making. Key gaps include how to mathematically extrapolate statistically meaningful data from small experimental data sets, corresponding to low TRL technology research, and how to meaningfully and usefully conduct knowledge extraction from technology experts.
Technology impact forecasting (TIF) as a science is still in its infancy, particularly in the engineering disciplines, such as aerospace. Simultaneously, the world is experiencing a dramatic increase in technology innovation. In an age where engineering designers are being asked to do more with less, a framework that enables the assessment of the system level impact of a low TRL technology would be invaluable as a means for enabling superior engineering design, as well as directing critical resource allocation. Specific gaps in the state of the art of TIF methods include how to mathematically represent combinations of impacts from several different or multi-functional technologies, how to merge probability distributions for different technologies while maintaining tra

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Final Report

Submitted to:

David M. Garner, PhD, PE
International Program Officer
AFOSR/EOARD
From the US: 011 44 189 561 6420
From Europe: +44 1895 616420
DSN: 314-235-6420

Submitted by

PhD Researcher: Ms. Ying Huang
Principal Investigator: Dr. Danielle Soban

School of Mechanical & Aerospace Engineering
Queen's University Belfast
Ashby Building, Stranmillis Road
Belfast BT9 5AH Northern Ireland
Tel +44 (0) 28 9097 4181
d.soban@qub.ac.uk

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Executive Summary

New aircraft are being required to meet increasingly stringent requirements, demanding that they be lighter, stronger, faster, and more environmentally friendly and sustainable, all at reduced operating costs. Multi-functional composites offer a possible solution to these conflicting design goals, and, through custom design and manufacturing techniques, could result in new materials that offer higher strength at lower weight. In addition, potential exists for bespoke capabilities, such as self-healing and damage detection, increased lightning strike protection, morphing wing shapes, and ice detection and prevention. The key challenge, and thus the novelty, of the research, is the extraction of meaningful data for a technology that is in its embryonic stage, and then being able to statistically extrapolate that data into a form that enables decision-making. Key gaps include how to mathematically extrapolate statistically meaningful data from small experimental data sets, corresponding to low TRL technology research, and how to meaningfully and usefully conduct knowledge extraction from technology experts.

Technology impact forecasting (TIF) as a science is still in its infancy, particularly in the engineering disciplines, such as aerospace. Simultaneously, the world is experiencing a dramatic increase in technology innovation. In an age where engineering designers are being asked to do more with less, a framework that enables the assessment of the system level impact of a low TRL technology would be invaluable as a means for enabling superior engineering design, as well as directing critical resource allocation. Specific gaps in the state of the art of TIF methods include how to mathematically represent combinations of impacts from several different or multi-functional technologies, how to merge probability distributions for different technologies while maintaining traceability, and how to propagate impact effects through a multi-scale model.

The information presented in this report represents the work accomplished during the one year funding period. This corresponds to the first year of research of a three year PhD dissertation. This report presents an overview of the Technology Impact Forecasting method, a summary of an extensive literature search into multi-functional composites with an emphasis on self-healing composite materials, and a test case of the TIF methodology to explore its appropriateness in producing useful results when operating on technologies of low technology readiness level (TRL), in this case self-healing composite materials.

The following conclusions were presented as outcomes of this research:

- For a wing comprised of 80% of self-healing material, there is an 80% confidence that aircraft takeoff gross weight will increase between 2.92% and 2.96% across the three different self-healing composite strategies analysed (traditional capsule based, wax-protection catalyst, CNT boosted). All costs were likewise increased:
    - RDT&E increased between 1.73% and 1.76%
    - O&S increased between 3.93% and 4.03%
    - First Unit increased between 16.36% and 16.57%
    - Average Unit Airplane Cost increased between 7.81% and 8.07%

- The results depend heavily on the shape factors, which represent the knowledge about (and the TRL) of the new technology under consideration. The above results were generated with a uniform shape distribution, meaning any value between the endpoints is just as likely as any other. When repeating the analysis by weighting the shape factors towards a more likely value within the same range, the 80% confidence results change to:

    - Takeoff gross weight increased on average 2.51%
    - RDT&E increased on average 1.26%
    - O&S **decreased** on average 13.54%
    - First Unit increased on average 5.88%
    - Average Unit Airplane Cost **decreased** on average 29.55%

- For low TRL technologies, which are represented by uniform shape distributions, the existing TIF method can be used in identifying trends or comparing across options.

- Mathematical methods to combine the effects of several technologies need to be further developed and incorporated into the existing TIF methodology.

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Nomenclature

ALCCA	Aircraft Life Cycle Cost Analysis
CFRP	Carbon Fiber Reinforced Polymer
CNT	Carbon Nanotube
DCPD	Dicyclopentadiene
DETA	Diethylenetriamine
DOE	Design of Experiments
ENB	Ethylidene Norbornene
FLOPS	Flight Optimization System
MWCNT	Multi-Walled Carbon Nanotube
ROMP	Ring-Opening Metathesis Polymerization
RSE	Response Surface Equation
TIF	Technology Impact Forecasting
TRL	Technology Readiness Level
UF	Urea-Formaldehyde

I. Introduction

To survive within today's stringent economic environment, aircraft design, particularly military aircraft design, has been experiencing a paradigm shift from an emphasis on design for optimum performance to design for system effectiveness [1]. As a consequence, designers and manufacturers are increasingly considering the addition of new technologies to aircraft design to reduce their cost, increase their operating capacities, and optimize new capabilities [2]. For next generation aircraft design, there are many innovative technologies to be developed that are financially constrained. However, infusion of a new technology (or technologies) are leading to another challenge: how does this new technology affect the aircraft system both in capability and economically? This is especially difficult because this new technology may not be completely defined until product implementation and service exposure occur. But in today's tight economic and limited resources environment, it is not possible to allow the designers to try out every technology on the aircraft system as this will result in low efficiency, time consumption and cost ineffectiveness. This issue is leading to another question: how to select an appropriate technology for the aircraft system before committing to the expense and risk of its full development? Obviously, it is essential to understand the benefits and/or penalties of a new technology to the system response before it is selected in order to reduce the research risk and budget. Therefore, designers need a forecasting environment which is able to rapidly assess the technical feasibility and economic viability for a given system before the technology is selected.

In addition, the life cycle phases of an aircraft design include conceptual, preliminary, detailed design, production, service and retirement [3], as is shown in Fig. 1. In the conceptual phase of the aircraft design, the design freedom is fully open for designers, yet only limited information is available for the new aircraft design. However, as design decisions are made, the design freedom rapidly decreases, while cost commitments increase [4]. Therefore, the key to success is "*making educated decisions (increased knowledge) early on, and maintaining the ability to carry along a family of alternatives (design freedom)*"[1].

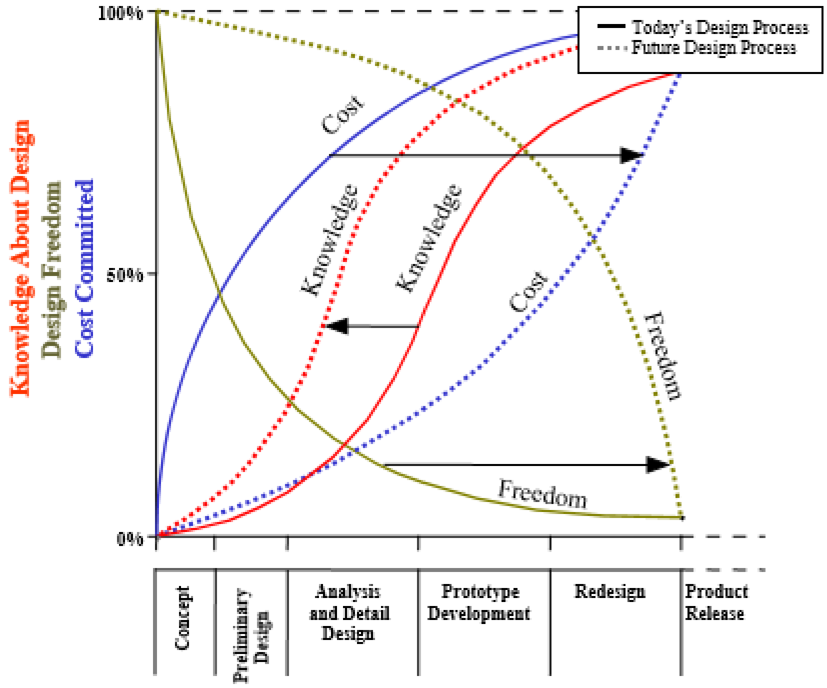


Fig. 1 Design Freedom Variation in Time [1]**.**

In response, a new methodology process known as Technology Impact Forecasting (TIF) has emerged, which is able to rapidly assesses the technical feasibility and economic viability of a new technology for a given system before this technology has been selected, thereby giving direction to further resource allocation [4]. This technique was developed about ten years ago and has mainly been applied to aircraft systems. TIF is a probabilistic method that not only emphasizes modelling and assessing the impact of technology infusion on a given baseline system, but also seeks to bring more knowledge about the system at an earlier stage of the design process. Although a solid background in initial TIF methods has been developted to mid Technology Readiness Levels (TRL)[5], it has never been applied to extremely low TRL technologies. Therefore, a goal of this research will be to assess whether the TIF process can be applied to low TRL technologies, or even to a notional technology, and still provide useful guidance for decision-makers, or whether the process needs to be substantially modified in order to be useful.

In this work, the assessment of the TIF methodology is to be conducted within a relevant application context – use of multi-functional composites for aircraft manufacturing. Next generation aircraft are expected to be stronger, lighter and fly faster while maintaining an affordable operational cost. These conflicting requirements dictate the development of new materials: multi-functional composites offer a possible solution. . These materials are capable of providing improved strength at a reduced weight and have other tailored benefits, including the ability to detect damage and self-heal, offer superior lighting strike protection, remove and ultimately prevent the build-up of ice, and change shape rapidly and consistently. However, the development of multi-functional composites is still in very low TRL (level 1-2). Low TRL is a key source of uncertainty and risk when considering techhnology infusion. Therefore, the second thrust of the proposed research is to create a mathematical and statistical model of the multi-functional composite technology to accurately capture and quantify the effects of this technology. This model will be based on existing, although sparse, experimental and physics-based data, as well as capturing and embedding subject matter experts' opinions in the field. The resulting model will be coupled with a systems level model and embedded into the enhanced TIF framework in order to to perform a complete system level assessment of proposed technology.

Therefore, this research will introduce a developed methodology framework which will be applied to a specific low TRL technology model of the multi-functional composites, enabling a complete system level assessment and quantification of the potential impact of the technology.

II. Literature Research

As an initial step in realizing this research, an overview of the existing TIF framework will be presented. Additionally, a literature search of the investigation on multi-functional composites materials will also be presented.

A. Technology Impact Forecasting (TIF)

The TIF framework is employed to minimize uncertainty and risk as a forecasting environment to predict the technical feasibility and economic viability of a new technology for an aircraft system before this technology is implemented, thereby giving direction to further resource allocation [3]. The current state of the art TIF has mainly been applied to aircraft systems.

1. Modelling and k-factors

At the heart of this method are models, which are comprised of both physics-based models and empirical models. The overall system can be represented by either one single model or more likely, a set of linked models at different system levels. A model can be used to assess changes to a given baseline system as a function of changes to inputs. For example, the question can be asked: how will the performance and capability of an aircraft vary if the designer replaces 50% of the aluminum structures with composite materials? To answer this question, a synthesis model of the baseline, or existing, system is created. The input variables of this model are considered the design variables which are in the control of the designer. A multiplicative factor, called a 'k-factor', is then added to each design variable. A grouping of design variables, together with their k-factors, is used to mimic the effect of a technology on a given baseline system [6]. For example, a new aerodynamic technology would be expected to affect the drag of an aircraft, but possibly also the lift and the weight. K-factors would then be assigned to the design variables that control drag, lift, and weight. The exact value of a k-factor for a new technology is not fixed, but rather presented a shape distribution, in order to represent the ambiguity and uncertainty associated with it. To take these uncertainties into consideration in constructing the model, variability must be added to each input variable. Therefore, a specific shape distribution is used for k-factors based on subject matter expert's opinions, as well as the exploration and extrapolation of historic technological data [4]. Finally, the outputs of the model are called the system responses, and are chosen to reflect the impact of this technology on a given system. Common examples of system outputs include aircraft takeoff weight, performance metrics, and cost. In this work, these k-factors will directly represent benefits and/or penalties of infusion of multi-functional composites on a baseline aircraft system. Since multi-functional composites represent an emerging technology, a complete knowledge about these k-factor is impossible. How to determine the k-factors and their ranges, and then use them to model the multi-functional composites has become one of research questions, and this question points to the need for a probability method.

2. Probability method

The reason for using a probabilistic technique is because a single point cannot completely represent the variability of a promising technology. In aircraft design, there are many inherent uncertainties and risks are present even with the most promising technology. Uncertainties root from lack of knowledge of the new technology, such as incomplete information, ambiguous requirements and variable performance and other unforeseen problems [1]. Using a probability shape function to respresent the variability of each k-factor associated with input variables of the TIF model would help designers to extrapolate sparse data and propagate these uncertainties through the TIF model [7]. For example, Fig.2 shows an example shape function for a k-factor in wing weight reduction. This particular shape function indicates that it is most likely to get a 7.5% reduction in wing weight, but anything between 6% or 9% is also possible albeit less likely. The type of shape funtion is based on the amount of knowledge available of the technology in question.

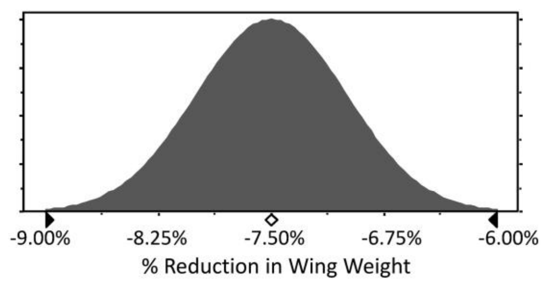


Fig. 2 Example of Shape Function [4]**.**

Shape functions are used in conjunction with a Monte Carlo method to run multiple instances of k-factors through the system model. The output, therefore, is not a single point, but rather cumulative probability distributions that indicate the percentage of confidence to achieve a desired outcome. If the probability value is high (generally,80% is an acceptable level of confidence) to achieve a desired result, the decision maker would most likely allocate appropriate research resources to further develop the technology. By associating output with liklihood of occurrence, the method allows the designer and the decision-makers to balance uncertainty and risk against potential outcome of the use of a technology. The probabilistic approach allows aircraft designers and decision makers to see how the system level responses vary with those new technologies in the early phase and to identify the worthiest of areas of investment [4].

TIF has been mostly developed for mid-TRL technologies over the past decade. Mid-TRL technologies allow for a better estimates of the initial shape function for the k-factors. Therefore there is a higher confidence in identifying an appropriate probability distribution associated with an mid-TRL technology. However, for the extreme low TRL technology, it is difficult to determine appropriate and accurate shape functions due due to lack of information. Therefore, the proposed research is to explore what is the best way to probabilitically model low TRL technologies, and feed it into the TIF framework.

3. Compatibility of technology

Assessing the impact of a single technology is quite straightforward, but often it is desirable to use more than one technology in a system at a time. The combination of several technologies into a comprehensive suite (also called a technology scenario s[8]) can be complex due to the compatibility and possible interactions between technologies. Some of these technologies cannot be added together without causing negative effects, or one technology may compete with the other in aircraft designs. For example, composites materials could help reduce the aircrafts total takeoff gross weight, but they lead to increased manufacturing, maintenance, repair costs and production learning curves. Existing TIFs simply add the effects of technologies into one technology scenario to assess the change they affect the overall system, and no interactions between the technologies are considered. As a follow on to this research, such interactions between different technologies will need to be investigated mathematically and the probability propagation will be considered.

4. Methodology

The overall TIF methodology [4] is depicted in Fig.3. There are totally eight steps, which will be discussed in details in the following paragraphs.

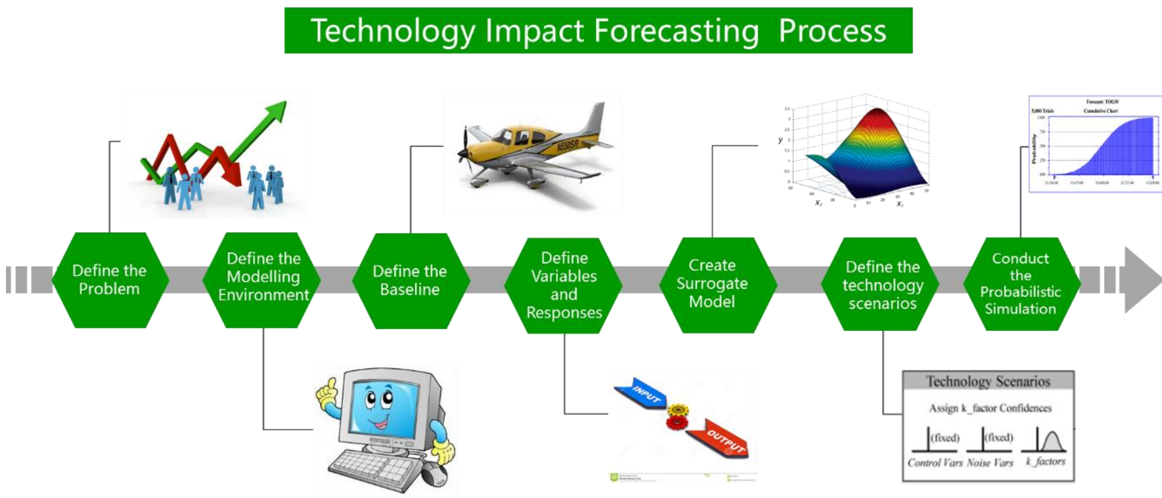


Fig. 3 The Technology Impact Forecasting process modified from [4]**.**

Step 1: Define the problem

The process begins with identification of the technology to be explored, and the context in which it is to be considered. Thought needs to be given as to what kind of information would be useful and relevant to designers and decision-makers.

Step 2: Define the modelling environment

The foundation of the TIF methodology is the overarching system model, which can be comprised of both physics-based models and empirical models. The overall system, aircraft, can be considered as a system-of-systems. It can be decomposed into several sub-models such as wings model, mission model, engine model, etc. Each of these sub-models can be further decomposed into its own sub-models. This concept is called multi-scale modelling [7]. Multi-scale modelling requires multidisciplinary metrics to evaluate the sub-model effects on overall system behaviour. Fig.4 shows an example of this concept.

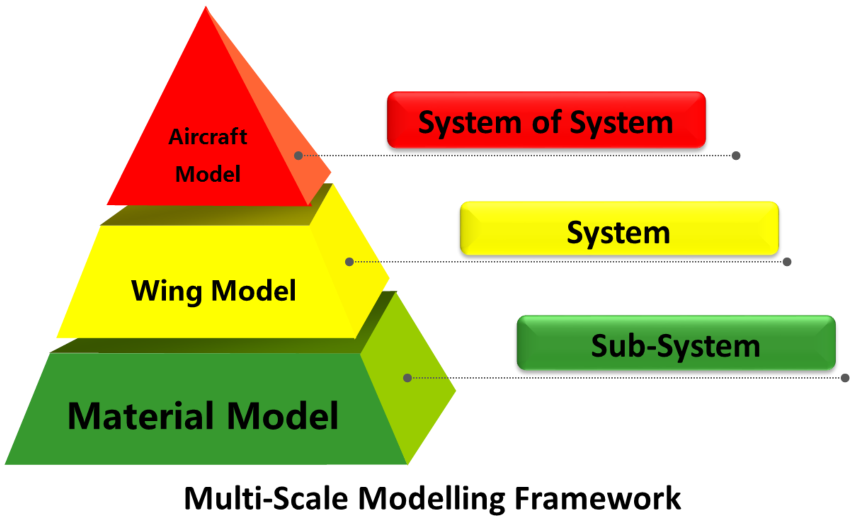


Fig. 4 Multi-scale Modelling framework of Technology Impact Forecasting.

Each of these models contains its own input variables and output responses. In this work, the starting model is a material model, the input of which describe the features of self-healing multi-functional composites, which are further represented by k-factors (multiplicative factors on key input variables). A wing model then takes the outputs from the material model to use as inputs, and then generates output to feed into a system level aircraft sizing and synthesis model. Hence, any assumptions of uncertainty and risks in the material model will be propagated all the way to the aircraft model to help decision makers to evaluate how well this technology meet the societal requirements [7].

Step 3: Define the baseline

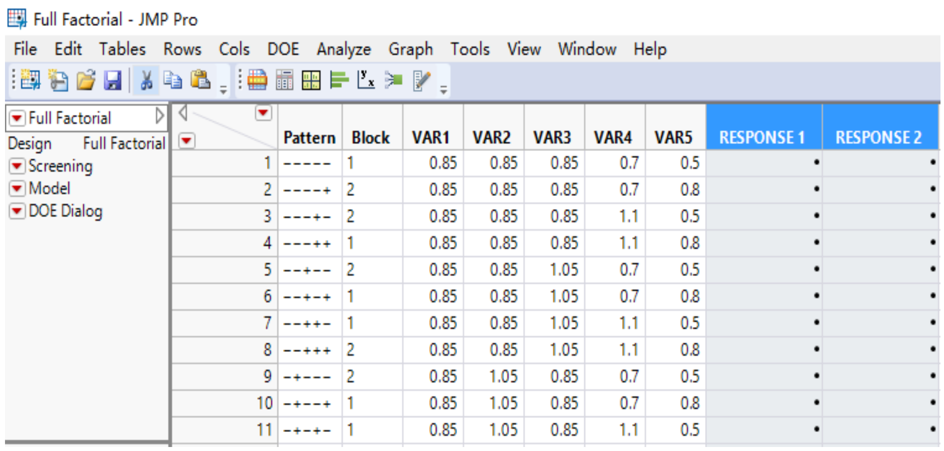
The baseline is defined as the unmodified system, before any addition of technology. This will normally be the state-of-the-art system. Results will be in the form of comparisons to this baseline, with quantified improvements or degradations. The modelling environment must be able to clearly model the baseline, as well as any relevant changes to it.

Step 4: Define the variables and responses

Variables (inputs) and responses (outputs) need to be identified for the overall system model, as well as each sub-model. The variables of interest to the analysis are selected as those key inputs that will be affected by the technology under consideration. Rather than manipulate the input variables directly, the TIF method manipulates the multiplicative k-factors. Usually these are represented as percentages of deviation. For example, a weight k-factor of -0.1 as applied to a structural variable would mean that the weight is reduced by 10%. The responses that vary with respect to changes in each of these variables are then selected in order to quantify how much the overall system would potentially be changed by infusing the technology. The same concept of inputs and responses apply for the wing and aircraft models. More specifically, the responses from material model are grouped together and substituted into a wing model as input variables. The wing configuration and performance are then assessed through the wing model, and its outputs translated into the aircraft model. The outputs from the aircraft model are then used to ultimately assess the impact of the technology on the overall aircraft system.

Step 5: Create Design of Experiments

This step often begins by conducting a screening test. If a large number of potential design variables exist, a first order screening test may be used to pare the variables down to those that make the most substantial impact on the responses of interest. This is especially important if the computational expense of the model is significant. After key variables are determined, a Design of Experiments (DoE) [9] is created, operating on the high and low boundaries of each k-factor, and often with the aid of statistical analysis software such as JMP [10]. The DoE is a systematic method used to determine the least number of computational experiments to run to yield the maximum amount of useful information. A DoE is created in a statistical software package and is given in the form of a table (Fig.5) that shows which combinations of variable to run through the simulation, in order to facilitate regression analysis.



	Pattern	Block	VAR1	VAR2	VAR3	VAR4	VAR5	RESPONSE 1	RESPONSE 2
1	-----	1	0.85	0.85	0.85	0.7	0.5	•	•
2	----+	2	0.85	0.85	0.85	0.7	0.8	•	•
3	---+-	2	0.85	0.85	0.85	1.1	0.5	•	•
4	---++	1	0.85	0.85	0.85	1.1	0.8	•	•
5	--+--	2	0.85	0.85	1.05	0.7	0.5	•	•
6	--+-+	1	0.85	0.85	1.05	0.7	0.8	•	•
7	--++-	1	0.85	0.85	1.05	1.1	0.5	•	•
8	--+++	2	0.85	0.85	1.05	1.1	0.8	•	•
9	-+---	2	0.85	1.05	0.85	0.7	0.5	•	•
10	-+--+	1	0.85	1.05	0.85	0.7	0.8	•	•
11	-+-+-	1	0.85	1.05	0.85	1.1	0.5	•	•

Fig. 5 Example of Design of Experiment.

Step 6: Run the Analysis Code

Using the DoE to determine the settings of the k-factors and the number of experimental runs, the model is executed and the resulting responses per experimental run parsed. In this case, FLOPS (Flight Optimization System) and ALCCA (Aircraft Life Cycle Cost Analysis) were used. FLOPS is a pre-existing aircraft sizing and synthesis computer code which was designed by NASA Langley Research Centre. It is a physics-based code that also uses aircraft historical data to model and simulated overall aircraft performance, structure and linked with ALCCA to determine the economic viability via varied variable inputs[11]. FLOPS and ALCCA were coupled with a bespoke materials and wing model to create the multi-scale modelling framework.

Step 7: Create the Surrogate Model

The outputs from FLOPS and ALCCA are used to create surrogate models, most often in the form of a response surface equation for each system responses as a function of the k-factors. Surrogate models are used instead of direct computational runs as they are computationally inexpensive and facilitate the Monte Carlo runs of the next step. A response surface equation [12] is often in the form of a second order quadratic equation:

$$R = b_0 + \sum_{i=1}^{x} b_i k_i + \sum_{i=1}^{x} b_{ii} {k_i}^2 + \sum_{i=1}^{x-1} \sum_{j=i+1}^{x} b_{ij} k_i k_j + \varepsilon \qquad (1)$$

R	= *Response term*
b_0	= *is the intercept term*
b_i	= *is the coefficient for linear term*
b_{ii}	= *is the coefficient for quadratic term*
b_{ij}	= *is the coefficient for cross-product term*
x	= *is the number of design variables*
k	= *is the design variables*
ε	= *is the error term*

The coefficient of each term can be obtained from least squares regression analysis using JMP. These equations can be used to infer a causal relationship between variables and responses. The Response Surface Equations (RSEs) are used to model all the possible system responses which are influenced by the technology infusion variables (k-factors). It incorporates the mathematical and statistical techniques to identify and evaluate the causal relationships between system responses and various variables [13]. RSEs seek to set the system response as a function of the design variables to optimize responses with any combination of design variables [13].

Step 8: Conduct the probabilistic simulation

Using the identified shape functions for each k-factor, the next step is to perform a Monte Carlo Simulation for each system response equations with statistical analysis software JMP [10]. The Monte Carlo Simulation is performed by randomly choosing variable values from the pre-assigned shape function and calculating the response through the Surrogate Model. The results are probability distributions that indicate the confidence to achieve required target values with use of the proposed technology. The shape function is dependent on the level of knowledge of the new technology, and is estimated from historical data, literature research, empirical results and subject matter expert's experience [4]. An example of the resulting probability distribution is shown in Fig.6. Given the shape function as input, the distribution shows that there is an 80% confidence to achieve a takeoff gross weight of 33725 lbs or less by using the technology. If the decision maker decides that 80% confidence is an acceptable risk to achieve this result, the decision maker would go ahead with the appropriate research resource to further develop this technology. Otherwise, the decision maker would shift their concentration to other technologies.

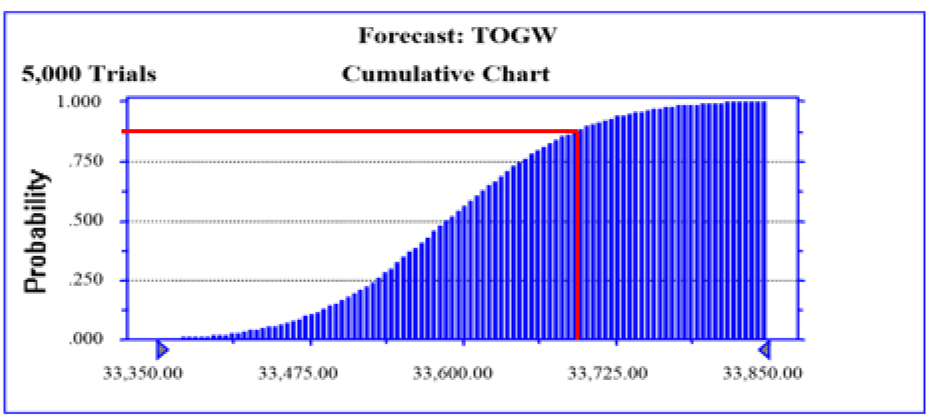


Fig. 6 Example of a Cumulative Distribution Function for Takeoff Gross Weight [7].

It is important to note that there is one cumulative distribution generated for each response in each technology. Assessing the impact of a single technology is quite straightforward, but often it is desirable to add more than one technology to the system at a time. Since the results are presented as a probability distribution, it is not valid to linearly sum the effects of two different technologies to assess their synergstic impact on a system. For example, what is the final system response under the scenario whereone technology increases the drag and the other technology decreases the drag? Future work of the research intends to address this issue.

B. Multi-Functional Composites

Next generation aircraft must be able to be stronger, lighter and fly faster while maintaining affordable operation costs. These requirements indicate a need for a new generation of engineered composites materials with multiple functionality and durability, named "multi-functional composites materials" [14]. As the name implies, multi-functional composites materials not only have all of the above exceptional properties, but also offer superior mechanical, electrical and thermal properties in order to perform multiple functional capabilities. As there is increasing interest with corresponding published research reports involving self-healing materials in recent years, it has been decided to choose self-healing materials as the first exemplar for low a TRL technology to assess its effects on a given baseline aircraft.

Self-Healing Materials

As a dramatic increase in the using of polymer matrix composites materials in aerospace parts, polymer matrix composites materials must have an ability to withstand various loading condition and thus long-term fatigue and corrosion damage. These kinds of materials will inevitably fail in the form of cracks or micro-cracks which induced by thermal and/or mechanical failure such as delamination, fibre-matrix deboning and matrix cracking. Cracks deep within the structure are often difficult to detect visually. Traditionally, structural composites require manual intervention for periodic inspection, damaged materials are repaired or removed by new material which result in expensive, intricate, time consuming maintenance and costly repair[15]. The demand for self-detectable and self-repairable of engineering material is common feature of many automotive, aerospace and military parts.

In order to lengthen the product lifetime, avoid catastrophic failure and save maintenance cost (base on economic perspective), scientist have explored the unique and efficient concept of self-healing processes since 1993[14], beginning with the source of inspiration from mimicking the feature of wound healing phenomena of human body's in biological healing system to autonomic responding and healing internal damage. A true sense of the concept of "self-healing" materials was proposed in the 1980s[16] as a means of healing invisible micro-cracks in order to lengthen the functional lifetime and safety of the polymeric components. Inspired by this healing strategy, Dry and Sottos first advocated for using a functional healing agent embedded inside the composites materials to recover their mechanical properties after damage[14]. This study has validated that it is possible to use a single hollow fiber as a storage container to release reactive healing agent into the fractured area to heal crack in a polymeric matrix. Motuku et al[17] have expanded this methodology into glass fiber reinforced polymeric composites by using hollow fibers made of borosilicate glass as microcapsules to adequately release healing agent to the damage site. An ideal self-healing material would possess the ability to heal in response to damage wherever and whenever it occurs in the materials. This unique ability not only eliminates the need for continuous monitoring, but can also quickly and effectively mitigate micro-cracks and hidden damage to sustain the performance of the materials.

The application of the various self-healing systems to composites materials requires a solid understanding of background of combining materials science, experimental and analytical mechanics and composites processing principles[18]. Self-healing systems are categorized into two groups: intrinsic or extrinsic[19]. As the name implies, intrinsic healing has ability to heal cracks by itself through its chemical nature. The intrinsic healing ability comes from interactions between polymer chains and reversible bonds to undergo the healing event upon an external stimulus such as temperature, electrical current or UV radiation, the sequestration of healing agent is no longer required. Therefore, intrinsic healing process is often defined as non-autonomous However, these non-autonomous healing processes are not commonly used in structural composites applications and therefore, details related to this will be not discussed here, the reader is referred to reference [20] for more information. In contrast to intrinsic healing, extrinsic healing requires built-in capability to transport liquid monomers which is often referred to as " healing agents "to the damage area and fill the site[18]. According to the architectural design of healing agent delivery system, extrinsic healing process can be classified into three groups: microcapsules based, hollow glass fibres and microvascular network [21].

1. Microcapsule

One of the most successful and extensively investigated completely autonomic self-healing system is accomplished by incorporating a self-healing agent filled spherical microcapsules and a catalyst (either solid or liquid) into the polymer matrix to polymerize the healing agent in the crack region[18]. A schematic of this autonomic healing concept is shown in Fig. 7.

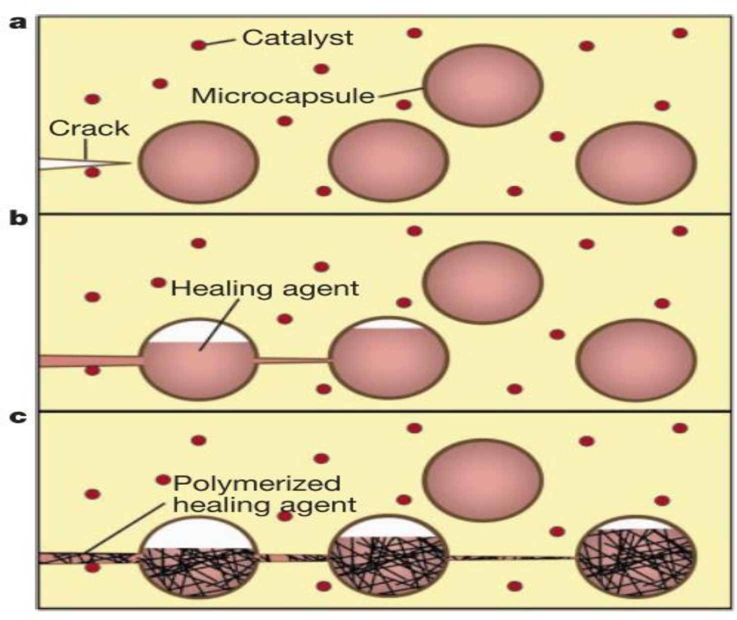


Fig. 7 Schematic of the microencapsulated self-healing system[18].

In this healing strategy, healing mechanism is initiate when cracks occur and propagate through the polymer matrix, it ruptures embedded microcapsules, leading to the release of healing agent into the crack region where subsequent polymerize with pre-dispersed catalyst particles in the matrix to adhere the two crack faces together[18].

Completion of this process requires a highly stable healing agent with sufficiently low viscosity to release healing agent into the damage area via capillary action to meet with embedded catalyst particles to heal or seal the cracks in the polymer[18]. The healing agent and catalyst must have the characteristics of long shelf life and low volatility without undergoing diffuse out the microcapsule wall, and also rapidly polymerized with surrounding catalyst particles at ambient condition in a reasonable time scale[18].

These combined characteristics are accomplished by using urea-formaldehyde (UF) microcapsules containing dicyclopentadiene (DCPD) healing agent that is polymerized by Grubbs' first generation (bis(tricyclohexyphosphine) benzylidene ruthenium dichloride) through ring-opening metathesis polymerization (ROMP) to form a newly high cross-linked secondary polymer, polydicyclopentadiene (polyDCPD) as filler to fill the gap between the two crack plane. White et al.[22]for the first time introduced this concept by dispersing DCPD-filled microcapsules and Grubbs' catalyst between plies of woven E-glass epoxy composites, resulting in 67% of cracking healing efficiency of its virgin fracture toughness. The optimal healing efficiency depends strongly on various parameters such as size and concentration of microcapsules, as well as catalyst concertation and dispersion[23]. So that for the self-healing system must include in higher concentration to increase the probability of a crack intersecting capsules, while using of the small diameter of microcapsules to overcome its negative effect on the Young's Modules and ultimate tensile strength of the composites[24][25]. In other words, the more embedded capsules are ruptured, the higher healing efficiency would be obtained. Interestingly, though, Brown et al. [26] indicated that the virgin fracture toughness can be significantly increased up to 127% with these additional polymeric microcapsules and this increment varied linearly with the microcapsules concertation until reaching a maximum value 15wt% capsule concertation. In addition, Rule et al.[24] indicated that the larger size microcapsules performed better than those with smaller microcapsules at the same weight fraction due to the amount of healing agent available for delivery to the crack plane. On the other hand, Brown et al. [26] have reported that smaller microcapsules exhibit maximum toughening at lower concentrations. All those extensive experimentation revealed that the size and concentration of microcapsules are crucial factor for the performance of the self-healing system, to balance the competing effects of the large size of microcapsules with it low concentration is the key to facilitate a high degree of healing efficiency. Another similar ROMP based monomers that have received significant attention with much faster polymerization rate while reducing the required amount of catalyst is ethylidene norbornene(ENB). It is recognized that ENB is capable to provide a more reactive healing system with shortest cure time within approximate 5 minutes with just 0.1wt% catalyst [22]. The main drawback of this method is that produce much more linear thermoplastic polymer with low strength which may result in loss of rigidity [23].

The largest drawback of using ROMP based self-healing is the high cost of Grubb's catalyst. This ruthenium-based olefin metathesis catalyst will likely never be cheap and their deactivated characteristics after exposure to amine-based epoxy's curing agent have become critical and challenging task. In addition, the reactivity of catalyst is extensively degraded during the fabrication of the self-healing polymer composites due to it contact with amine-based epoxy curing agents (e.g. diethylenetriamine (DETA)) used in self-healing epoxies. This degradation of chemical activity may dramatically reduce the healing efficiency and even results in no ability to heal the cracks [27]. In order to improve healing efficiency and isolate the contact of the catalyst with DETA during epoxy curing process, Rule et al [28]have shown that by encasing the catalyst into paraffin wax microspheres serve the dual purposed of preventing deactivation of those catalyst from detrimental interaction with DETA, and improving the dispersion of the catalyst throughout the polymer matrix. More importantly, by using these waxed catalyst, the amount of costly catalyst required in a self-healing polymer can be decreased 10-fold to achieve similar level healing efficiency to an unwaxed catalyst [28]. Fracture testing results have shown that a maximum average healing efficiency of 93% was reported with only 0.75wt% catalyst concentration.

To summarize, the self-healing system via microencapsulation is by far the most studied self-healing concept in recent years. The various constituent materials in the self-healing system must work compatibly without negatively affecting each other. The stoichiometric ratio of each constituent materials is varied with a view towards optimization of the recovery of structural composites properties. As mentioned above, the performance of capsuled self-healing materials is designed upon the volume of healing agent could deliver to a crack plane. The encapsulated volume of healing agent is limited and once the microcapsule is fractured and released, the local healing agent is depleted and cannot be refilled which restricts the number of healing agents that can occur. Therefore, efforts have been made to introduce repeatable delivery of the healing agent in the damage area to enhance healing efficiency.

2. Hollow fibres

Hollow fibers are a discrete architectural design of healing agent delivery systems providing the repeatable delivery of healing agent in the fractured area when compared with capsule-based healing systems. Unlike capsule-based healing systems, the two components of healing chemistry, the healing resin and resin hardener, are both infused into separate hollow fibres. During a damage event, healing resin and resin hardener are both diffused from broken hollow fibers into the damage region and initiate repairing mechanism through polymerization to impede the crack propagation and recover the mechanical properties of the matrix [29](Fig.8). These hollow fibres in here not only act as a structural reinforcement, but also can be used as a container to store large volume of healing agent.

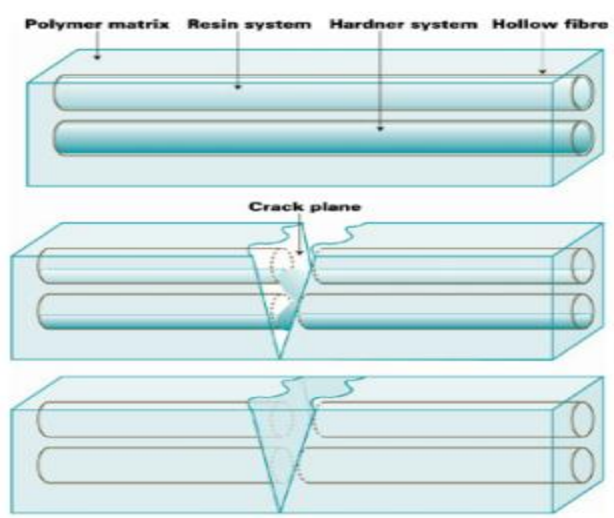


Fig. 8 Schematic of self-healing concept with hollow fibre [21]**.**

The challenge of this method is to balance the competing effects of disruption of the composites laminates by embedding large diameters of hollow fibres and enhancing the healing efficiency by delivering an adequate volume of healing agent to address any damage. Bond et al [30] who manufactured hollow glass fibres with diameters between 30 to $100\mu m$ with hollowness greater than 50% were filled with healing resin and incorporated into either glass fibre-reinforced polymer (GFRP) or carbon fiber-reinforced polymer(CFRP). Hollow fibres can be incorporated as additional plies at most vulnerable interface or distributed within individual plies of composites laminate e.g. CFRP[31]. Although, hollow glass fibres were preferred for their storage ability to carry the reactive healing agent in composites laminate without negatively affect the host laminate, they are often used for secondary structures on airplane such as wing tips and helicopter rotor blades. In addition, CFRP are gradually taking the place of metal alloy in most of primary structures of modern aircraft with its reliability performance and low density, distribute hollow glass fibres within GFRP plies will produce a hybrid glass-carbon laminate which significantly reduce their mechanical properties.

3. Vascular Systems

Unfortunately, the self-healing system via microcapsules and hollow fibres are both restricted the healing agent volume that can delivery and the number of healing events that can occur. To address these problems, extension work has shifted the target towards to design a more bloodflow like healing system with refillable healing agent from a pervasive interconnected channel which act as a reservoir to continuous deliver healing agent to the damage region, this novel self-healing system have been referred as “microvascular” network as shown in Fig. 9.

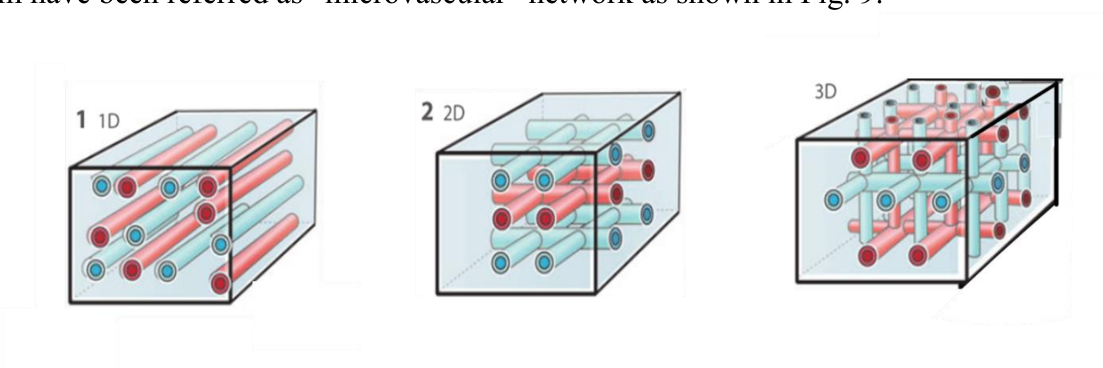


Fig. 9 Schematic diagram of self-healing martials with microvascular networks[32]**.**

The healing chemistry of this method is same as microencapsulated self-healing system through ROMP with embedded Grubb’s catalyst in the epoxy matrix contact with flowing DCPD monomer in the microvascular to recover up to 70% fracture toughness [33]. However, this healing microvascular network does not have the feasibility in advanced CFRP composites process, such interconnected channels will disturb the composites laminate architecture and greatly reduce overall structural performance. Also, due to their sophisticated fabrication technique and very expensive production have obstructed their feasibility and practicality to the fibre-reinforced composites[34].

4. Multi-Functional Composites System

Next generation aircraft must be able to be stronger, lighter and fly faster while reducing fuel cost and maintaining affordable operation costs. These requirements indicate a need for a new generation of engineered composites materials with multiple functionality and durability ,named "multi-functional composites materials"[35]. The emergence of the CNT multi-functional composites could offer possible solutions to these conflicting requirements. CNT multi-functional composites are built upon traditional carbon fiber reinforced polymer composites (CFRP) and mix carbon nanotubes with district properties in order to improve the aircraft structural properties, reduced weight, as well as introducing other functionalities, such as fatigue resistance, defect sensing and corrosion suppression, and preventing lightning strikes [36]. Recently, Jeong and Kessler have developed processes that use multi-walled carbon nanotubes (MWNT) as nanofillers to improve mechanical and adhesive strength of the ROMP based healing agent system. The tensile toughness can be increased up to 900% compared to neat polyDCPD at MWNT loadings just 0.4wt% which is not affect the viscosity of the healing agent[37]. Moreover, carbon nanotubes have even been considered to utilize as a container to store and release the healing agents for automatic repairing application[38]. However, this methodology still requires extensive experimentation to explore its feasibility in the structural composites process to meet industrial needs.

Conclusion

This section has summarized a series of recent results in the fields of self-healing composites materials, introduced various self-healing concept and systems and discussed potential problems to achieve optimal healing efficiency. Despite the large number of published articles which are related to variations in healing agent delivery technique and polymerization kinetics, there are only a few of them indicating successful fabrication of self-healing composites. Due to limited reliable experimental data, the details of these research were not discussed herein. The future work of self-healing materials is to develop ideal healing system with repetitive healing event, enhanced mechanical performance, elegant fabrication process and cost effectiveness to translate this technology to practical application. In the area of aircraft application, there is potential future in using this type of materials to increase the durability and reliability for the aircraft components, thereby reduce its maintenance cost.

III. Application of TIF to Self-Healing Materials

Although there is an ever-increasing body of published literature on self-healing composite materials, the low TRL of this new technology means there is a lack of repeatable substantiated data on which to operate. The research question becomes:

Can the TIF methodology generate useful information for designers and decision-makers, when operating on the scant and uncertain data corresponding to a low TRL technology?

To test this question, the TIF methodology was used to attempt to assess the impact of self-healing composite materials on a baseline aircraft system.

A. Modelling Environment

In this case, the outputs from a model of self-healing composite materials are not able to directly map as inputs to an aircraft model because there is not enough fidelity around the inputs of an aircraft model to show the variability of self-healing technology on the aircraft system. In other words, typical inputs for an aircraft sizing and synthesis code do not include detailed material property variables. Hence, an intermediary model is needed to take the material properties from self-healing model as its inputs to conduct its analysis and generate outputs that serve as inputs into the aircraft model. Ultimately, there will exist two models: one is self-healing model and another one will be a wing model. Each model contains its own set of algorithms, database and relationships. Ultimately, these two individual models are grouped together to provide suitable inputs for the aircraft model. Any change at the self-healing model can be thus be propagated through wing model all the way up to the aircraft model.

For the self-healing model, the monomer DCPD and Grubbs' first-generation catalyst were selected for self-healing system undergoes ROMP reaction. Carbon fiber-reinforced polymer (CFRP) composites (100kg) were used to demonstrate a fully self-healing structural composites system utilizing the concept that described in last section. The unidirectional carbon fiber was used as fiber reinforcements with 200 g/m^2 arial weight. The composites matrix was fabricated by mixing EPON 828 epoxy resin with 12 pph diethylenetriamine (DETA). Sixteen plies of composites panels with central four self-healing plies were manufactured by hand lay-up and compression molding. For none self-healing plies, carbon fabric was impregnated with neat resin using a hard plastic applicator. For self-healing plies, DCPD filled microcapsules at various loadings by weight (10-25%) and Grubbs' catalyst (2.5-5%) were stirred into the resin and then applied with a 50mm brush to prevent rupture of the microcapsules during resin application. Next, the panel was compressed in a tetrahedron (MTP-14) hot press at 2225N at 25℃ for 24 hours, followed by postcuring at 30℃ for 48 hours. The resulting panels is sketched as shown in Fig. 10. Additional details of this method can be found in reference [39]and relevant physical and mechanical properties are list in Table 1.

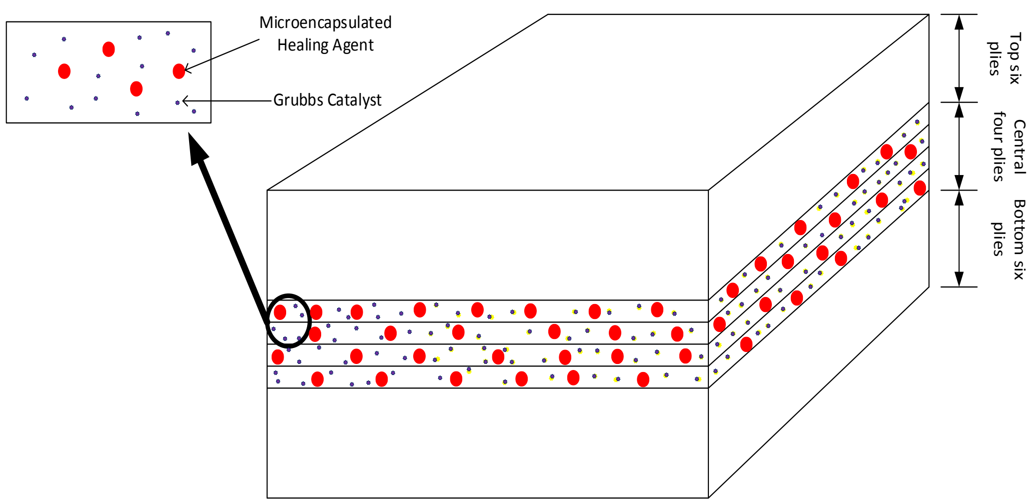


Fig. 10 Schematic of Self-Healing CFRP Composites

Table 1 Properties of the Constitution

Constituents	Density (kg/m^3)	Concertation	Young's Modulus (GPa)	Price (£/kg)	Price ($/kg)
DCPD	1000	10-25 (wt.%)	-	164	228
Catalyst	N/A	2.5-5 (wt.%)	-	71900	99941
Wax	900	3.75-4.5(wt.%)	-	43	60
MWCNT	2100	0.05-0.4(wt.%)	1 (TPa)	1118	1554
Epoxy	1160	50-40(vol.%)	3.4	165	230
Carbon Fibre	1800	50-60 (vol.%)	228	-	-
CFRP	1500	-	137.88-115.35 (Parallel) 5.34-6.63 (Perpendicular)	-	-

The self-healing model was created through Visual Basic Software within Microsoft Excel, database was created using experimental data which was collected from large number of publications involve various aspects of self-healing materials in recent years. It is worth noting that it is not practical to collect all the data from these publications, since the aim of this study is to create novel mathematical model that will allow system level quantitative assessment the impact of self-healing materials on a complex aircraft system. Therefore, experimental data were selected from representative articles in each of the relevant categories. Along with the increase in the number of publication in self-healing progression technology and method for the fabrication, self-healing model only focus on three common healing methods: capsule-based, wax-protected catalyst microsphere, CNT boosted. The next step was to take these data to perform a regression analysis to create polynomial representations to determine how the healing performance vary with respect to change in each of constituent material's stoichiometric ratio. Finally, it was necessary to investigate the economic viability of the utilization of this self-healing materials for a given system before they are infused into aircraft system.

For intermediary wing model, because the internal algorithms of wing model in FLOPS is not able to use to account for undefined technology such as self-healing materials, therefore the baseline values of wing weight had to pull out from FLOPS and substitute into self-healing model to investigate its variation for different healing method. And afterwards, the results had to put back into FLOPS to assess the potential benefits and/or penalties of infusing self-healing materials for aircraft system. A user created input file was fed into the FLOPS/ALCCA program via a shell script to facilitate automatically multiple runs and change input variables. Then, the results of calculation were exported from FLOPS/ALCCA and extracted by wing model for further analysis.

B. Baseline Aircraft

The aircraft baseline used for this study was a short-medium-range commercial transport aircraft Airbus A320-200 (Mach 0.78), carrying 150 passengers to destination within 3000 nautical miles and annual utilization in excess 3800 block hours. The reason this aircraft was selected as the baseline is that it employs a relatively high percentage of composite materials compared to other aircraft which is an essential condition that must be met for this study since self-healing capability is built on composites materials. The relevant wing's geometric design parameters of A320-200 are given in Table 2 and subsequently substitute into FLOPS as input data to conduct its analysis.

Table 2 Selected Characteristic Data of Baseline Aircraft.

FLOPS Code	Description	Value
TR	Taper Ratio of the Wing	0.24
SPAN	Wing Span (ft)	117.5
SW	Reference Wing Area (ft^2)	1330
FSTRT	Wing Strut-Bracing Factor (0-1)	0
SWEEP	Quarter-Chord Sweep Angle of the Wing (Degree)	25
AR	Wing Aspect Ratio	9.39
FAERT	Decimal Fraction of Amount of Aeroelastic Tailoring Used in Design of Wing (0. to 1.)	0
TCA	Wing Thickness-Chord Ratio (Weighted Average)	0.082
ULF	Structural Ultimate Load Factor	3.75
FCOMP	Composite Utilization Factor for Wing Structure (%) (0. to 1.)	0.5-0.8
NFUSE	Number of Fuselages 1.0 for a Single Fuselage ,0.5 for Multiple Fuselages	1
VARSWP	Wing Variable Sweep Weight Penalty Factor (0. to 1.)	0
PCTL	Fraction of Load Carried by Defined Wing	1
FLAPR	Flap Ratio -- Ratio of Total Movable Wing Surface Area (Flaps, Elevators, Spoilers, etc.) to Wing Area	0.2569

C. Model Assumptions

The economics software program ALCCA program was used to analyse and estimate all the life cycle cost associated with self-healing CFRP composites. All economic analyse was performed in 2017 US dollars and average annual inflation rate is assumed at 3.95% base on dollars of 1970. The exchange rate for Pounds to US Dollars used was 1.39. Table 3 displays the ALCCA economic assumptions made within this study. Note: vales in Table 3 are referenced from Unitde States Department of Labor, "May 2017 National Industry-Specific Occupational Employment and Wage Estimates".

Table 3 ALCCA Economic Assumptions

ALCCA Input	Description	Value
API	Average Annual Inflation Factor (%)	3.95
RE	Engineering Labor Rate ($/hr)	55.43
RT	Tooling Labor Rate ($/hr)	27.05
RL	Maintenance Labor Rate, ($/hr)	30.53
AFSPAO	Airframe Spares for Production (%/100)	0.06
ENSPAO	Main Engine Spares for Production (%/100)	0.23
NV	Operational Vehicles Demanded	640

It was assumed that the wings of the aircraft would be split between composites and aluminium materials only meaning a percentage increase in composites would incur a similar percentage decrease in aluminium and vice versa. The FCOMP (composites utilization factor for wing structure) input variable within FLOPS program was used to define the percentage of composites within the wing structure, and its corresponding the learning curves for manufacture and assembly of aircraft wing were used to model the system complexity for adding the self-healing materials into the system. Table 4 display the material assumptions made of the aircraft wing within this study and its corresponding learning curve.

Table 4 Material Assumptions and Learning Curve Based on FCOMP

FCOMP	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Learning Curve (%)	85	85.5	86	86.5	87	87.5	88	88.5	89	89.5	90

D. Variables and Responses

Once the model environment and its baseline had been clearly identified, the design variables and system responses were selected for each model. For self-healing model, these are measures of weight (weight increased after adding various constituent of self-healing materials in the composites system), performance (Young's modulus of composites materials after adding the capability of self-healing) and economics (cost of self-healing materials). Hence, the variables of interest to the analysis need to be selected that can model changes in each self-healing methodology (capsule-based, wax-protected catalyst microsphere, CNT boosted). Once the variables have been selected, suitable ranges need to be defined. Likewise, the system responses that vary with respect to change in each of these variables need to be selected in order to quantify the potential benefits and risks associated with self-healing materials. Table 5 summarized the input variables and their range for self-healing model and table 6 lists the responses chosen for self-healing model and later, in turn generates these output that serve as inputs into wing model.

Table 5 Input Variables and Ranges of Variability Examined for Self-Healing Model.

Variables	Minimum	Maximum
Weight fraction of DCPD (%)	10	25
Weight fraction of Grubb's catalyst (%)	2.5	5
Fibre volume ratio in CFRP (%)	50	60
Neat epoxy fracture toughness(MPa)	0.5	0.6

Table 6 Tracked Responses for Self-Healing Model.

Response	Description
Performance	Young's modulus of CFRP after adding self-healing materials (in the direction parallel to the fibres(GPa) (Youngs1)
	Youngs modulus of CFRP after adding self-healing materials (in the direction perpendicular to the fibres(GPa) (Youngs2)
Weight	Weight increased of CFRP after adding self-healing materials
Economics	Cost of self-healing materials

For the wing model, a change in the wing manufacturing labor learning curve and wing manufacturing materials learning curve were selected as input variables to mimic the manufacturing complexity. The outputs from wing model consisted of basic wing structural weight and its economic viability, which was directly be mapped as inputs variables into the aircraft model (FLOPS).

The output data from FLOPS was used to assess and quantify the impact of self-healing technology when they are infused into aircraft system, as shown in Table 7. These outputs at the aircraft model will be based on three areas chosen below. The first consideration was aircraft sizing such as total take-off gross weight (TOGW), operating weight empty (DOWE), fuel weight (FUEL WT) and wing loading(W/S). Economic changes were identified as second area such as RDT&E, first unit cost, average unit airplane cost, operation and support cost. Finally, performance responses of aircraft were selected as last area to show the changes in certain capabilities of the aircraft.

Table 7 Responses of Interests from FLOPS

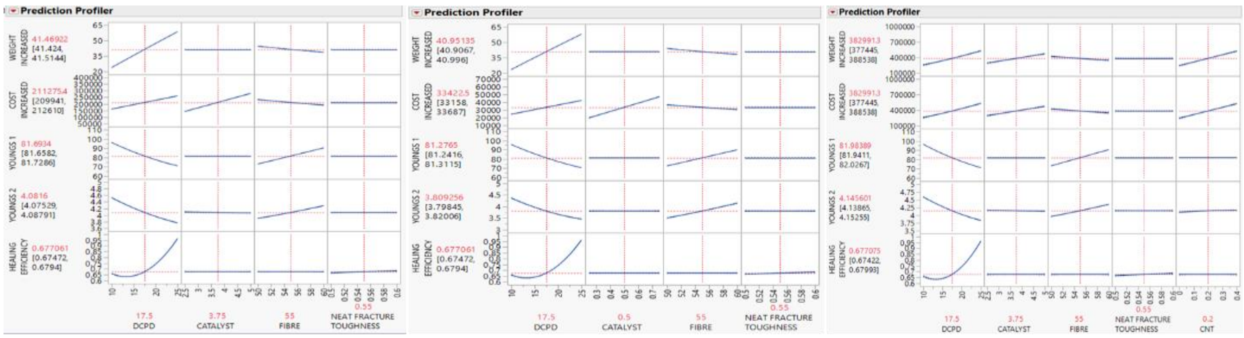
Responses	Description	Baseline	
		FCOMP (0.5)	FCOMP (0.8)
TOGW	Take-off Gross Weight (lbs)	154849.1	152684.2
DOWE	Operating Weight Empty (lbs)	77751.9	76136.1
FUEL WT	Fuel Weight (lbs)	45747.1	45198.1
W/S	Wing Loading (lbs/ ft^2)	116.43	114.8
THRUST	Engine Thrust (lbs)	23227.4	22902.6
RDT&E	Research, Development, Testing and Evaluation Cost (M$) (excluding the aircraft production cost)	7461.29	7408.49
TOC	Operation and Support Cost (M$)	37.75	39.74
FUC	First Unit Cost (M$)	234.97	253.50
AUAC	Average Unit Airplane Cost (excluding spares) (M$)	104.55	119.93

E. Results

A visual tool called "prediction profile" was used to create the basis of the TIF environment. The prediction profile is a feature of JMP software which is mainly used to graphically see how the output responses vary with respect to change in those input variables by mapping variables against responses. The gradient of the hairline indicates the sensitivity of the response that is influenced by that variable and the direction of the hairline indicates either a positive or negative influence. The vertical axis contains all the responses of interest, and the horizontal axis contains each of the variables. The prediction profile also allows the designer to adjust the values of a variable by moving the hairlines, and the corresponding values of the response are updated immediately. In this way, the designer can conduct "what if "games with the various engineering requirements.

1. Self-Healing Model Results

In order to determine these cause and effect relationship between each variable and its system response for each self-healing method, the response surface equation for each system response was constructed using the statistical software package JMP. To create these response surface equations, a Design of Experiments (DoE) table was performed which was used to select a subset of variables combinations for each experimental run. In addition, it is not necessary to do screening test since the variables of interest were few enough in number that their retention did not significantly affect the computation run time. The model runs with a central composite design only consisting of 44 model runs. The self-healing model results are presented in the form of a prediction profile (Fig.11). These results corresponded to the decision of stoichiometric ratio of each constituent material are needed to tailor structural composites properties for specific self-healing method to obtain optimum healing performance with lightest composites weight at the lowest cost.



(a) Capsule-based

(b) Capsule-based with wax-protection catalyst

(c) Capsule-based with CNT boosted

Fig. 11 Prediction Profiles for Self-Healing Model

As shown in Fig. 1, the fit shapes for three self-healing methods show the same trends. The first thing to notice is that none of the fracture toughness of neat epoxy have a significant impact on system responses because the line is flat. This indicates that fracture toughness of neat epoxy is not a player and can be removed from further analysis. The same result is seen with fibre volume ratio in CFRP for healing efficiency, but it affected Young's modulus of CFRP composite which is make sense because fibre volume fraction is a very important mathematical element to determine overall mechanical properties of a composite. A higher fibre volume fraction will results in better mechanical properties of the composite[40]. The weight fraction of Grubb's catalyst seems to be a major contributor to the cost of self-healing materials due to its high cost which is same as previously discussed. Interestingly, the weight of DCPD shows considerable effect on the all responses. First, DCPD have a quadratic effect on the healing efficiency, this is because the quadratic mapping relationships that was used to determine the healing efficiency of self-healing materials. Moreover, increasing the weight of DCPD gives negative influence on the Young's modulus of CFRP composites which is a good proof of the previous conclusion that higher concentration of encapsulated DCPD in composites matrix may increase the probability of a crack intersecting capsules and release large volume of healing agent into the damage area thus enhance the healing efficiency, but it easily causes poor bonding to the matrix and disrupt the inherent properties of composites. The last thing is that as the weight of DCPD increases, the cost and weight of CFRP composites are also increased which a logical and expected result.

For a new technology concept e.g. self-healing material, there are many inherent uncertainties and ambiguities are present with regards to its performance due to its incomplete information, insufficient experimental data and other unforeseen problems. To take these uncertainty into the model, its variability must be added to each input variables using probability shape function. In this case, the actual form of shape function is unknown due to the limited knowledge that exists in using self-healing material. Therefore, a uniform shape function (Fig. 12) was assigned for each input variables to run Monte Carlo Simulation with 5000 time of analysis to get a robust statistical analysis at this fidelity level, result is the Cumulative Distribution Function (CDF) for each system response that indicate the confidence of achieving a certain value (Fig. 13). To read these CDFs, an 80% confidence level is assumed to be an appropriate confidence interval and read cross to see the value achieved.

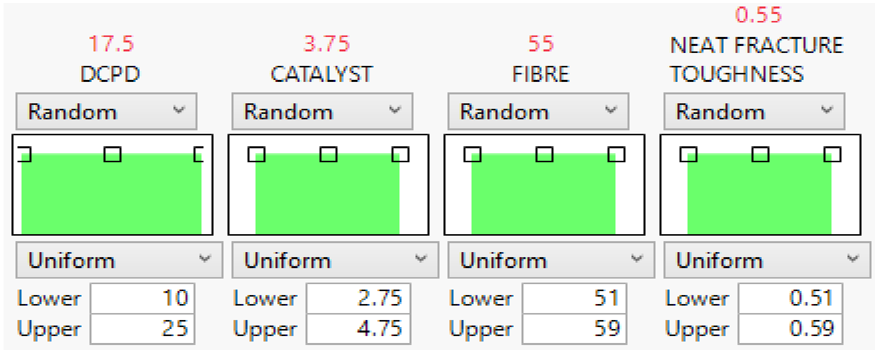


Fig. 12 Sample of Assumed Shape Functions for Self-Healing Materials

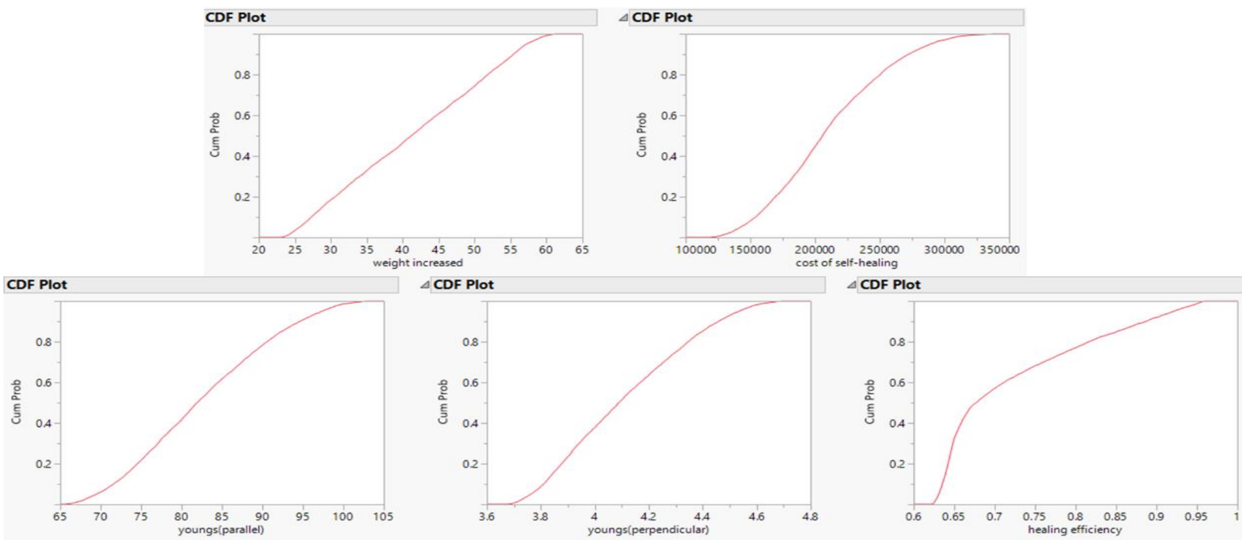


Fig. 13 Example of CDF for Self-Healing Materials

After running the TIF methodology with self-healing material technology, the results are summarized into the Table 8. It is clear from the table that the CNT boosted self-healing material has highest cost increment $708755 per 100kg of composites with average healing efficiency of 78% was achieved. This may be due to its high strength, low weight of CNT and its associated high production process cost. The self-healing of capsule-based with wax-protection catalyst shows the lowest cost increment, it is only one ninth cost of the CNT boosted self-healing materials with same level of healing efficiency. The Young's Modulus of CFRP composites was partly decreased when incorporated these healing materials, this negative impact may restrict their application in the area of aircraft design. Overall, the self-healing with wax-protection method gives the best effectiveness results.

Table 8 Comparison of Results for Three Self-Healing Materials

Responses	Capsule-based	Capsule-based with wax-protection catalyst	Capsule-based with CNT boosted
	80% probability	80% probability	80% probability
Weight of CFRP composites increased/100kg(kg)	49.88	48.97	50.29
Cost of CFRP composites increased/100kg ($)	344001	83012	708755
Youngs modulus of CFRP composites after adding self-healing (parallel)(GPa)	88.47 (-23.3%~-35.8%)	87.83 (-23.9%~-36.3%)	88.61 (-23.2%~-35.7%)
Youngs modulus of CFRP composites after adding self-healing (perpendicular)(GPa)	4.34 (-18.7%~-34.5%)	4.05 (-24.2%~-38.9%)	4.33 (-18.9%~-35.6%)
Healing efficiency of fracture toughness	78%	78%	78%

2. Wing Model Results

It is worth to mention that this wing model is a preliminary analysis tool which is only used to generate outputs from the self-healing model that serve as inputs to the aircraft model (FLOPS). Therefore, the output from this model will directly be mapped as inputs variables into the wing model. Because there is no discernible effect of Young's Modulus of CFRP composites and self-healing efficiency on the performance of wing in FLOPS/ALCCA, so, these variables were eliminated from this level analysis. It should be noticed that ALCCA is a weight-driven economic program, the economic responses will change as the aircraft weight is varied, and therefore the wing model here focuses more attention on the variation of wing weight.

Table 9 Comparison of the Wing Weight for Different Self-Healing Method

	FCOMP	Baseline	Capsule-Based		Wax-Protection Catalyst		CNT Boosted	
Weight of Wings (lbs)	0	15351.4	15351.4	0.00%	15351.4	0.00%	15351.4	0.00%
	0.1	14873.8	15257.78	2.58%	15253.112	2.55%	15260.292	2.60%
	0.2	14397.6	15140.972	5.16%	15131.777	5.10%	15145.674	5.20%
	0.3	13923.6	15001.948	7.74%	14988.378	7.65%	15008.533	7.79%
	0.4	13451.2	14840.216	10.33%	14822.438	10.19%	14848.395	10.39%
	0.5	12980.8	14656.351	12.91%	14634.547	12.74%	14665.852	12.98%
	0.6	12512.1	14450.162	15.49%	14424.528	15.28%	14460.729	15.57%
	0.7	12045.2	14221.898	18.07%	14192.643	17.83%	14233.293	18.17%
	0.8	11580.1	13971.7	20.65%	13939.046	20.37%	13983.7	20.76%
	0.9	11116.8	13699.705	23.23%	13663.889	22.91%	13712.104	23.35%
	1	10655.1	13405.803	25.82%	13367.075	25.45%	13418.411	25.93%

The calculated weight of aircraft wing results for different healing method are compared in Table 9. The model was calculated based on 10 wt. % of DCPD with 2.5 wt. %, 0.75wt. % of catalyst for capsuled-based and wax-protection respectively, and 0.4% of functional MWCNTs for CNT boosted method, while all other variables were held constant. Each column state wing weight as percentage of change from its baseline values. The tendency of weight increment for each self-healing methods are quite same, as the fraction of composites materials used in the wing increases which lead to the total percentage of self-healing materials are also increased, it results in additional weight in wing components. By combining these results with previous results from self-healing model, the conclusion can be made at this point that the self-healing material with wax-protection catalyst shows the best technical feasibility and economic viability for aircraft wings. Unfortunately, CNT boosted self-healing method shows less promised to aircraft wings due to its high cost of production process. However, this may or may not reflect reality, because CNT boosted self-healing method is a novel concept, there are only limited database for this method and thus it may not be completed identified, therefore the attention must be paid when considering the use of this method.

3. Aircraft Model (FLOPS/ALCCA)

So far, the preliminary methodology framework for low TRL technology has been created and the wing's data have been substituted back to FLOPS/ALCCA for further analysis and use. Several additional variables with its specific range were chosen to conduct system analysis in response to model the increased complexity of using this self-healing materials to the aircraft system. Thus, the economic effect was also modelled as changes in the wing manufacturing labor learning curve and wing manufacturing material learning curve. Notably, there is a new factor was used to model the maintenance decrement by using self-healing materials. The assumption was made that the number of airframe and systems maintenance man hours needed per flight hour was reduced about 4-8% by using self-healing materials. This is due to its attempt to extend structural materials lifetime, which partly reduce the man hours needed for periodic inspection and so the cost of operation will decrease. Since the critical value of these variables are unknown, therefore care must be taken that the range of these variables are wide enough to capture the effect of interest. Typically, an assumption must be made for each these variables within this study and then using probability shape function to account for variation in their assumption. Table 10 compiles all the variables used in aircraft model as well as its range of these variables used.

Table 10 Input Variables for FLOPS/ALCCA

<table>
<tr><th>Variables</th><th colspan="2">Description</th><th colspan="2">Baseline</th><th>Low</th><th>High</th></tr>
<tr><td>CFWCO</td><td colspan="2">Complexity Factor for Composite Wing Structure Basic Design Engineering</td><td colspan="2">1</td><td>0.8</td><td>1.5</td></tr>
<tr><td>CFWCOTF</td><td colspan="2">Complexity Factor for Composite Wing Tooling and Factory Test Equipment</td><td colspan="2">1</td><td>0.8</td><td>1.5</td></tr>
<tr><td>CFWINGCO</td><td colspan="2">Wing Structure Composite Complexity Factor</td><td colspan="2">0.502</td><td>0.4</td><td>1</td></tr>
<tr><td>Learning Curve (%)</td><td colspan="2">Learning Curve Factor</td><td colspan="2">82</td><td>85</td><td>90</td></tr>
<tr><td rowspan="3">FRWI</td><td rowspan="3">Total Wing Weight (lbs)</td><td>Capsule-Based</td><td>11580.1 (FCOMP=0.8)</td><td>12980.8 (FCOMP=0.5)</td><td>13971.7 (FCOMP=0.8)</td><td>14656.35 (FCOMP=0.5)</td></tr>
<tr><td>Waxed</td><td>11580.1 (FCOMP=0.8)</td><td>12980.8 (FCOMP=0.5)</td><td>13939.05 (FCOMP=0.8)</td><td>14634.55 (FCOMP=0.5)</td></tr>
<tr><td>CNT Boosted</td><td>11580.1 (FCOMP=0.8)</td><td>12980.8 (FCOMP=0.5)</td><td>13983.7 (FCOMP=0.8)</td><td>14665.85 (FCOMP=0.5)</td></tr>
<tr><td>Maintenance</td><td colspan="2">Reduction of maintenance man hours needed per block hour due to infuse self-healing materials</td><td colspan="2">-</td><td>0.04</td><td>0.08</td></tr>
</table>

Having defined these input variables for FLOPS/ALCCA, as well as assuming their range and their system responses of interest in previous section, a DoE table was created to specify which values of these variables to run for each experimental run. Again, it is not necessary to conduct the screening test to eliminate the variables in this case, because the number of variables are fewer that did not affect the computation run time. Next, response surface equations were created by running these variables combination which were defined in DoE table to establish a cause-and-effect relationship between these variables and system responses, and the sample result is shown in the form of prediction profiles in Fig. 14.

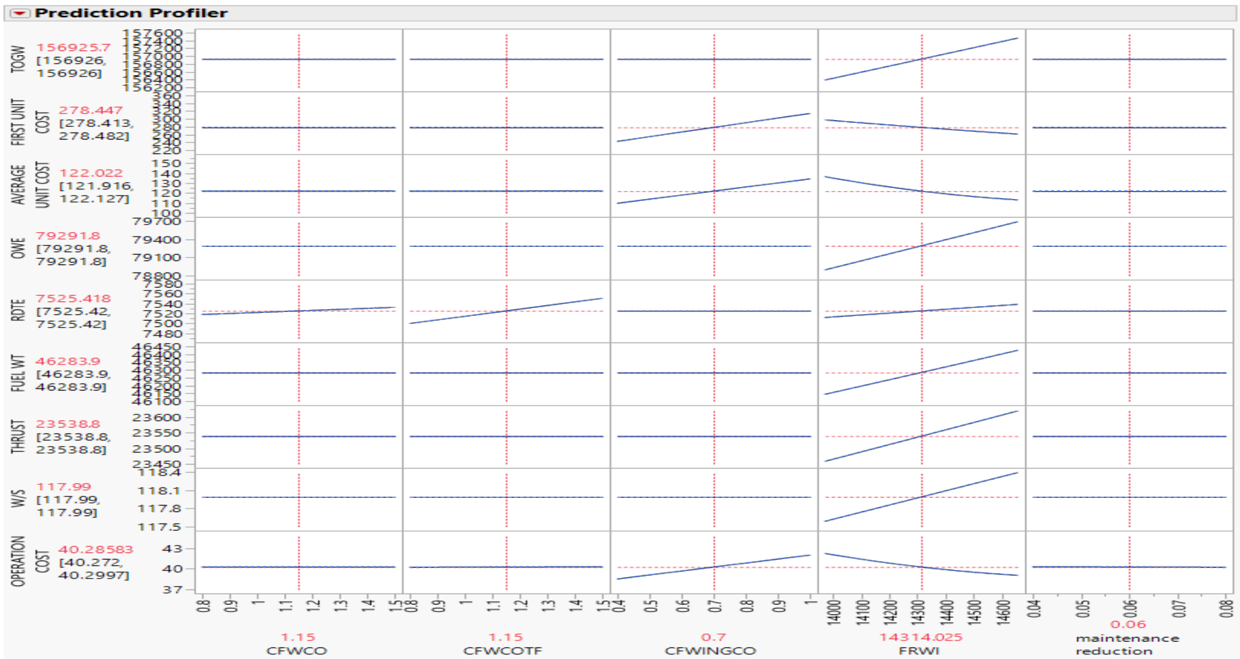


Fig. 14 Sample of Prediction Profile for Aircraft System

Since the three self-healing methods have the same trends to the aircraft system responses, only one sample will be discussed. Investigation from left to right, CFWCO has a slight effect on the RDT&E cost, which makes intuitive sense. As the difficulty of designing composites wing structure with self-healing ability for aircraft engineer increases, so the cost of research, development, testing and evaluation increases. And same trend is seen for CFWCOTF, but notice that the effects is bigger from a slightly higher sloped line. This is because by adding self-healing ability to composites wing structure will increase in total number of man hours required to build and test airplane. CFWINGCO have a significant effect on the cost of manufacturing and operation. For airplane where the wing structure is made with composites materials, the cost of materials to manufacture the airplanes will increase due to its high cost of fibre reinforcement and production process. The most interesting variables is FRWI (total wing weight) which play a dramatic influence on all the system responses. As the weight of wing increases, the performance and size of aircraft increases. All of these make intuitive sense. For example, an additional weight of self-healing materials was added to aircraft wing result in the increasing of the total wing weight and same for take-off gross weight and operating weight empty. The next response that affected by total wing weight is wing loading. Remember, the wing loading is equal to the ratio of total wing weight and wing area. Because the wing area is set constant for baseline aircraft, therefore the wing loading increases as total wing weight increases. In addition, as the wing weight increases it required more power to propel the aircraft go forward, therefore the engine thrust is also increased. Interestingly, the opposite effect is seen for operation cost which provided as proof of assumption that using self-healing materials would extend material's service lifetime and increases in durability and reliability, thereby reduce the man hour needed for maintenance and periodic inspection. At the same time, manufacturing - first unit cost and average unit aircraft cost both decrease as the weight of wing is increased which may or may not reflect its reality because of the interactive effect between various variables. In light of this sample, it is clear that it is not valid to linearly sum the effects of different variables to assess their synergistic impact on a system. This has point out that a further analysis is necessary to find an appropriate mathematically way to combine the effect of various input variable to assess their combinatorial impact on a system.

Finally, even though these types of materials can be used to reduce the man hours needed for maintenance process, they did not have much positive influence on overall system responses. There is a trade-off between additional cost by using this self-healing in commercial aircraft system and the potential cost of failure. Therefore, the further investigation is needed to explore the possibility of using self-healing materials in military aircraft system. Because the aim of commercial aircraft is to obtain greater profit for stakeholder, yet the aim of military aircraft design is to complete its mission and increase its combat survivability. It not difficult to imagine the time saving from repairing the aircraft during the combat by using self-healing materials. Again, self-healing material is still low TRL technology containing inherent uncertainties and risks when considering technology infusion on an aircraft system. In order to introduce these uncertain and risk into the analysis, it is not enough only use a single number to represent its variability, it is more likely to set a probability shape distribution for each input variables to model a possible changing within a certain range. In this case, uniform distribution was assigned for each of the input variables since each value was equal likely to occur. Next, Monte Carlo Simulation was performed by randomly choosing variable values based on assigned distributions and calculate through response surface equations that have built earlier on to form a cumulative probability distribution for each system responses. The sample result is shown in Fig. 15 and its side-by-side compared results are given in Table 11.

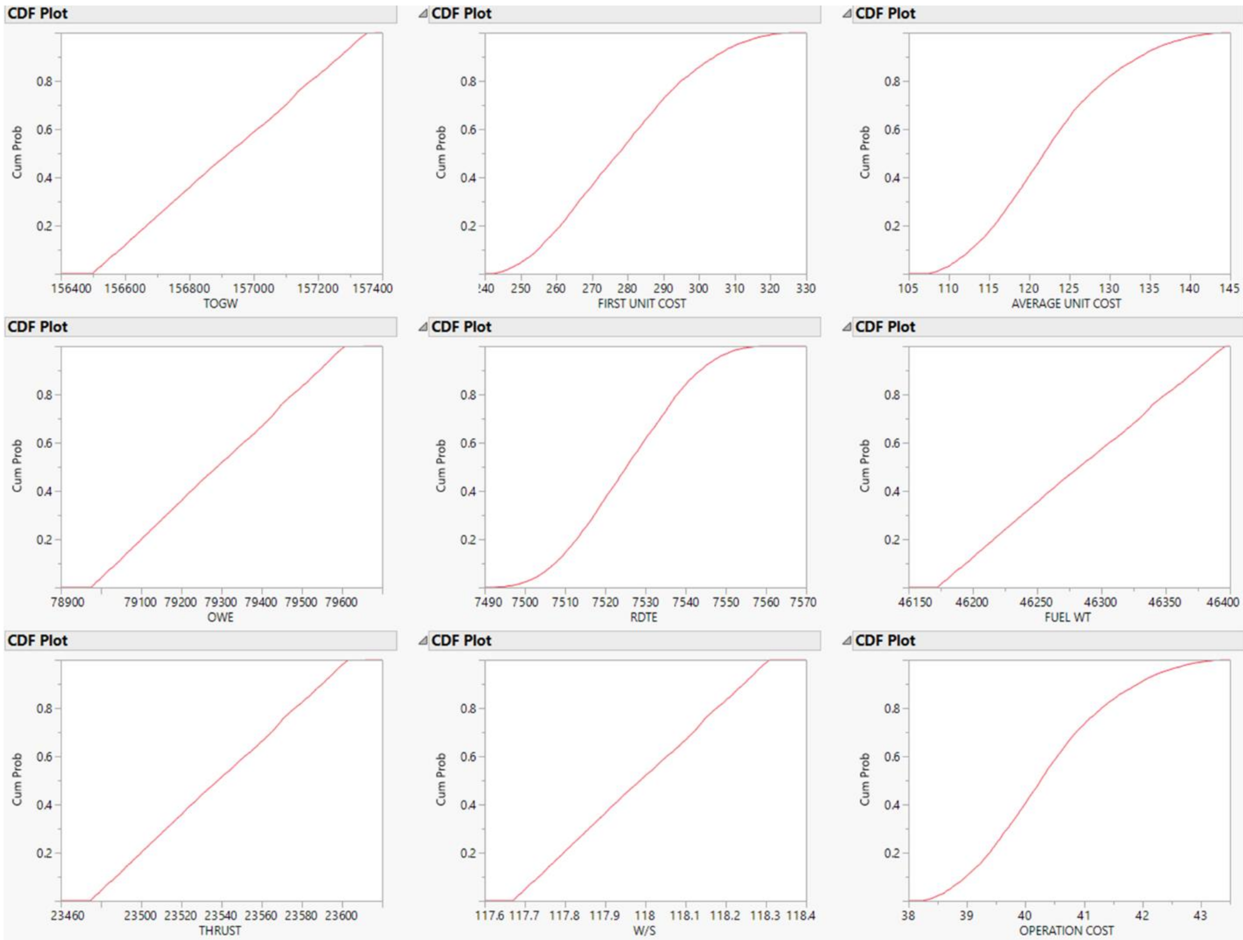


Fig. 15 Cumulative Probability Distribution Results for Capsule-based Self-Healing Materials

Table 11 Comparison Result for Three Self-Healing Materials on the Baseline System

Responses	Baseline		Self-Healing Materials											
	FCOMP (0.5)	FCOMP (0.8)	Traditional Capsule-Based				Wax-Protection Catalyst				CNT Boosted			
			50% Prob.	Effect (%)	80% Prob.	Effect (%)	50% Prob.	Effect (%)	80% Prob.	Effect (%)	50% Prob.	Effect (%)	80% Prob.	Effect (%)
Take-off Gross Weight (lbs)	154849.1	152684.2	156930.2	1.34~2.78	157186.6	1.51~2.95	156879.6	1.31~2.75	157136.3	1.48~2.92	156953.1	1.36~2.80	157206.4	1.52~2.96
Operating Weight Empty (lbs)	77751.9	76136.1	79295.13	1.98~4.15	79484.16	2.23~4.40	79257.85	1.94~4.10	79447.23	2.18~4.35	79311.98	2.01~4.17	79498.75	2.25~4.42
Fuel Weight (lbs)	45747.1	45198.1	46285.08	1.18~2.4	46352.38	1.32~2.55	46271.74	1.15~2.38	46339.09	1.29~2.52	46291.08	1.19~2.42	46357.63	1.33~2.57
Wing Loading (lbs /ft^2)	116.43	114.8	117.99	1.34~2.78	118.18	1.51~2.95	117.96	1.31~2.75	118.15	1.48~2.92	118.01	1.36~2.80	118.2	1.52~2.96
Engine Thrust (lbs)	23227.4	22902.6	23539.48	1.34~2.78	23577.96	1.51~2.95	23531.96	1.31~2.75	23570.47	1.48~2.92	23542.97	1.36~2.80	23580.96	1.52~2.96
RDT&E (M$)	7461.29	7408.49	7525.37	0.86~1.58	7538.4	1.03~1.75	7524.25	0.84~1.56	7536.3	1.01~1.73	7525.65	0.86~1.58	7538.51	1.03~1.76
Operation and Support Cost (M$)	37.75	39.74	40.25	6.62~1.28	41.30	9.40~3.93	40.27	6.68~1.33	41.34	9.51~4.03	40.29	6.73~1.38	41.31	9.43~3.95
First Unit Cost (M$)	234.97	253.50	277.51	18.10~9.47	294.97	25.54~16.36	277.87	18.26~9.61	295.51	25.76~16.57	278.15	18.38~9.72	295.28	25.67~16.48
Average Unit Airplane Cost (excluding spares) (M$)	104.55	119.93	121.83	16.54~1.58	129.30	23.68~7.81	121.95	16.64~1.68	129.61	23.97~8.07	122.02	16.71~1.74	129.33	23.70~7.84
Self-Healing Materials Cost (M$)	-	-	6.17	-	6.66	-	1.96	-	2.12	-	14.03	-	15.2	-

It is clear from the Table 11 that there is an 50% likelihood of achieving the lowest take-off gross weight of 156880 pounds or less by using self-healing materials with wax-protection catalyst method on the aircraft wings which is 2.75% higher than its baseline value based on using 80% of composites materials on aircraft wings, and it corresponding RDT&E is higher by almost 1.56%. This is due to the additional weight of self-healing materials used and the associated high cost as discussed earlier. So, the analyst can conclude that, the self-healing materials with wax protected catalyst is going to be considered as a best method for controlling the weight and cost of aircraft. In order to achieve this take-off gross weight, engine must put on more thrust to overcome this weight and so there is 50% chance to achieve an increasing of a thrust of 23531.96 pounds, but a 2.92% increase in engine thrust could be obtained with an 80% chance and also fuel weight is increased simultaneously with engine scaling at a 2.52%.

For economic responses, it can be concluded that the lowest increment in manufacturing-first unit cost is 9.47% by using self-healing materials with traditional capsule-based method with a 50% confidence. Again, this is because the extensive used of costly self-healing materials. This trend may result in a higher acquisition prices and ticket fares for commercial aircraft. There is a 50% chance of achieving an average unit airplane cost of 121.83 million dollars by adding traditional capsule-based self-healing materials based on the 640 production unit manufactured, but there is an 80% chance of achieving an increment of an operation cost of 3.93% or higher. Overall, even though the self-healing materials does reduce the maintenance cost, but at a penalty of increased aircraft weight and all the economic responses.

F. Discussion

The results, therefore, showed that it is risky for commercial aircraft when considering use this self-healing materials on the system, because the stakeholder benefit is priority for commercial aircraft. Since the self-healing materials is a multistep, intricate and very expensive low TRL technology for the aircraft system, it is no surprise that all the economic responses of the aircraft are increased. Once this technology is validated in relevant environment, in other words, once it gets more mature and steps up to mid TRL level, the cost of economic responses is expected to be much lower or breakeven. As mentioned earlier, the probability shape distributions have been set up to represent its variability for each input variables and shape functions that had been used in this test case were uniform shape functions, this is because the actual technological impact of self-healing materials is not known yet. It is clear that the selection of an appropriate shape function is a key enabler for each variable because it can heavily influence the subsequent Monte Carlo Simulation and the final results. In addition, even though this self-healing materials is not mature yet to its full development, there is no doubt it can hugely impact modern aircraft systems in future. Clearly, this result has shown possible impacts of this technology on capabilities and costs which become a clear requirement for the material experts to explore technology improvement in the areas of weight, cost and performance. The question to be considered now is: how much improvement of this technology is needed to meet those requirements? In other words, to play 'what if' games. To answer this question, we need return to the TIF environment and manipulate the shape functions for each input variables with smaller range, re-run the analysis to see if the results are favourable. Also, manufacturing learning curves have to decrease to 80%-82% to meet the economic requirement. Now, the man hours reduced for maintenance process through using self-healing materials are assumed within 50%-60%, while this may not be accomplished at current level technology states. But in order to obtain optimal economic goal and objectives, it is necessary to set this value to be idealized. Run the analysis again with new shape functions and smaller ranges (Fig. 16) and the optimal results are summarized in Table 12.

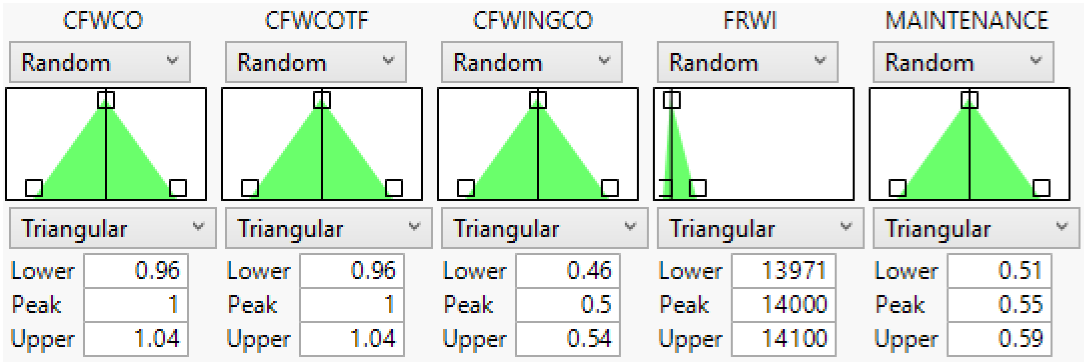


Fig. 16 Manipulated Shape Function for Input Variables

Table 12 New Results for Self-Healing Materials Technology Using Improved Shape Functions

Responses	Baseline	Self-Healing Materials											
		Capsule-Based				Wax-Protection Catalyst				CNT Boosted			
	FCOMP (0.8)	80% Prob.	Previous Results	diff	Qualitative Effect	80% Prob.	Previous Results	diff	Qualitative Effect	80% Prob.	Previous Results	diff	Qualitative Effect
Take-off Gross Weight (lbs)	152684.2	156513.53	157186.6	2.51%	Better	156499.81	157136.3	2.50%	Better	156516.16	157206.4	2.51%	Better
Operating Weight Empty (lbs)	76136.1	78987.06	79484.16	3.74%	Better	78976.92	79447.23	3.73%	Better	78989.04	79498.75	3.75%	Better
Fuel Weight (lbs)	45198.1	46176.48	46352.38	2.16%	Better	46172.89	46339.09	2.16%	Better	46177.12	46357.63	2.17%	Better
Wing Loading (lbs /ft^2)	114.8	117.68	118.18	2.51%	Better	117.67	118.15	2.50%	Better	117.68	118.2	2.51%	Better
Engine Thrust (lbs)	22902.6	23476.98	23577.96	2.51%	Better	23474.95	23570.47	2.50%	Better	23477.4	23580.96	2.51%	Better
RDT&E (M$)	7408.49	7501.96	7538.4	1.26%	Better	7501.58	7536.3	1.26%	Better	7501.98	7538.51	1.26%	Better
Operation and Support Cost (M$)	39.74	34.37	41.30	-13.51%	Better	34.32	41.34	-13.64%	Better	34.39	41.31	-13.46%	Better
First Unit Cost (M$)	253.50	268.66	294.97	5.98%	Better	267.61	295.51	5.57%	Better	268.97	295.28	6.10%	Better
Average Unit Airplane Cost (excluding spares)(M$)	119.93	84.55	129.30	-29.50%	Better	84.27	129.61	-29.73%	Better	84.65	129.33	-29.42%	Better
Self-Healing Materials Cost (M$)	-	6.66	-	-	-	2.12	-	-	-	15.2	-	-	-

It is clear from this new table that the overall cost of aircraft has decreased, particularly in operation cost due to the assumption are made that by using self-healing materials into the aircraft system could extensive reduce of man hours needed for maintenance. In light of this example, the materials experts now can go back to the research field with clear goal to develop a more durable and reliable self-healing materials to extensive reduced the maintenance cost, therefore, to obtain optimal result. Overall, the conclusion can be made at this point that by adding the self-healing materials into the aircraft system might increase the initial cost of aircraft, but produces significant cost saving in the long run.

IV. Conclusion

An initial comprehensive literature research and a mathematical model for determining the quantitative impact of low TRL technology on a complex aircraft system has been presented.

Technology Impact Forecasting (TIF) process offers a forecasting environment that allows the designer to rapidly assess the impact of the technologies on the aircraft system by using probabilistic technique. A brief overview of a current Technology Impact Forecasting methodology framework has been introduced. However, shortcomings in the mathematical formulations of the models lead to their limited usefulness in extremely low TRL technologies. It is clear that an enhanced TIF process needs to be developed that may be applied to low TRL technologies. The development of these new methods needs to be conducted in the context of a relevant application. As increasing published reports that involving of self-healing materials in recent years, it has been decided to choose self-healing materials on the multi-functional composites as our first low TRL technology to assess its effects for a given baseline aircraft. It is clear from this test case that using this self-healing materials on the system is risky for commercial aircraft, but better results are expected for further technology development.

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